Measurements of $|V_{ub}|$ and $|V_{cb}|$ at BABAR

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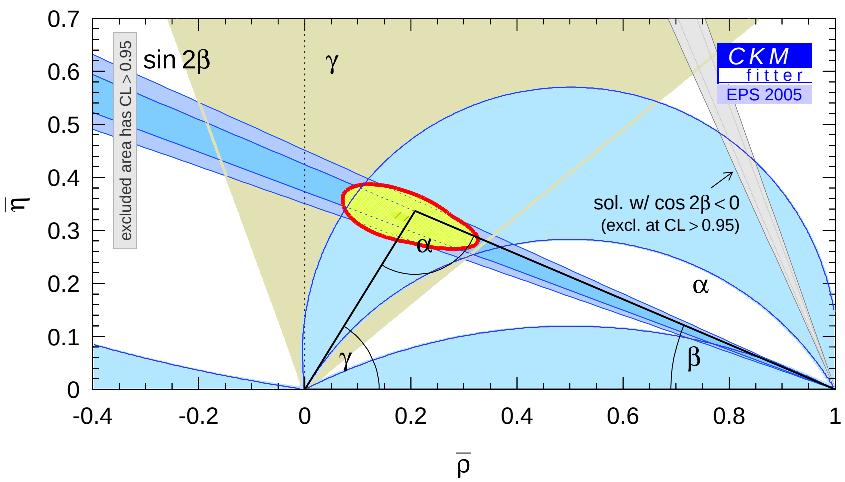
(on behalf of the BABAR Collaboration)

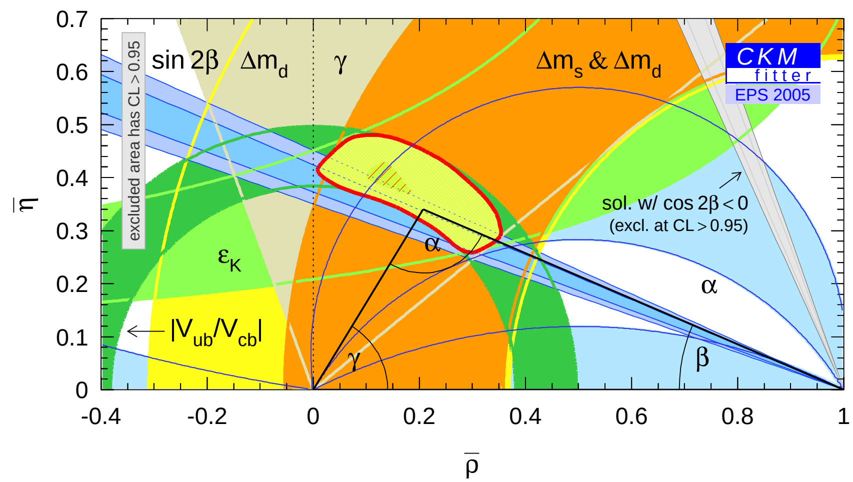
Motivations

- B **factories has improved our understanding of CP violation :**
  - ◇ $sin\ 2\beta = 0.687 \pm 0.032$ **(a precision measurement of 4.7%)**
  - $\hookrightarrow$ **This precision outstripped the other measurements**

- **As for today measurements $|V_{ub}|$ and $|V_{cb}|$ are complementary to $sin\ 2\beta$**



◇ **Using only angle measurements**



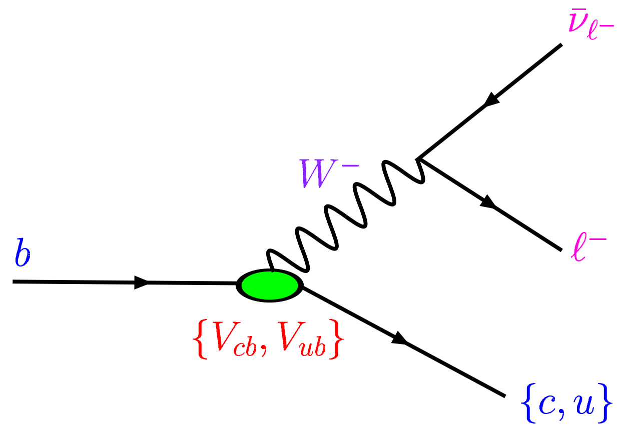
◇ **Without angle measurements**

- **It is clear that we have to make the green ring ($\frac{|V_{ub}|}{|V_{cb}|}$) thinner in order to make a stringent test on the Standard Model**

- **We need to improve a precision of $|V_{ub}|$ (especially) and $|V_{cb}|$**

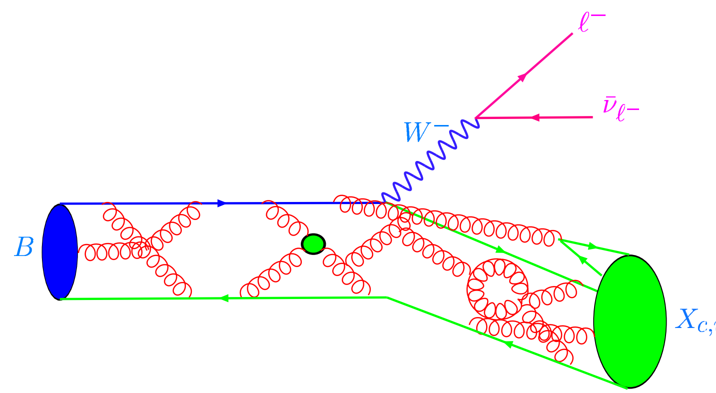
Semileptonic B Decays

♢ Why do we use semileptonic B Decays ?



- ☐ Simple theoretical description at parton level
- ☐ B flavor can be identified from charge of lepton
- ☐ Coupling at W^- is propotional to $|V_{ub}|$ and $|V_{cb}|$ which is directly related in its decay rate :
  - $\Gamma(b \to u\ell\nu) = \frac{G_F^2}{192\pi^2}|V_{ub}|^2 m_b^5$
  - $\Gamma(b \to c\ell\nu) = \frac{G_F^2}{192\pi^2}|V_{cb}|^2 m_b^2 (m_b - m_c)^3$

♢ Experimental Approaches :



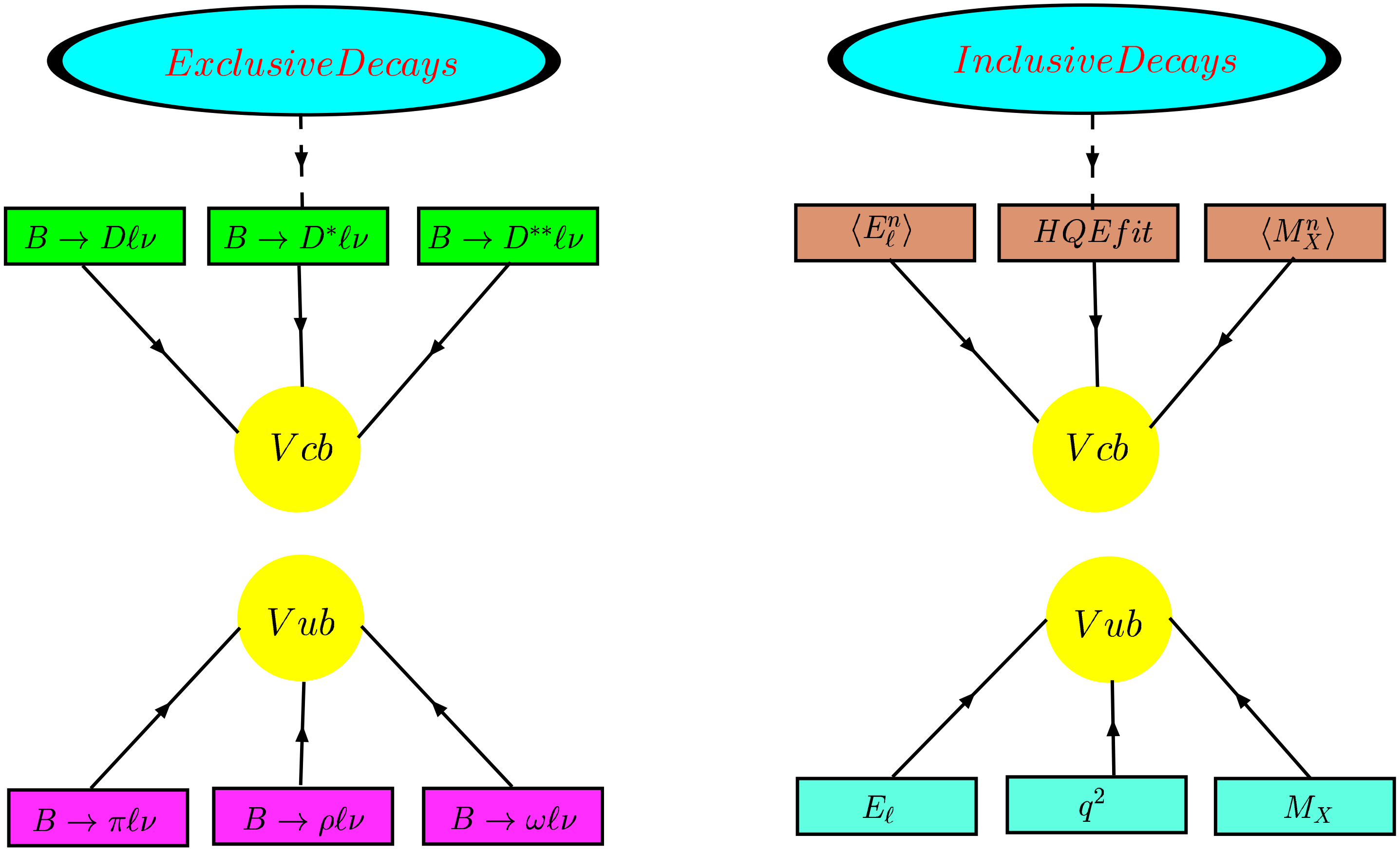
- ☐ Sensitive to strong interactions in B decays
  - Exclusive measurements

    need form factors to describe the B transition
  - Inclusive measurements

    need Operator Product Expansion (OPE) and b mass to extract $|V_{xb}|$

Exclusive and Inclusive Diagram

♢ Experimental Description



- **Lepton Energy Moments :** $M_\ell^{(n=2,3)} = \frac{\int_{E_{cut}}^{\infty} (E_\ell - M_\ell^1)^n d\Gamma}{\int_{E_{cut}}^{\infty} d\Gamma}, \quad M_\ell^1 = \frac{\int_{E_{cut}}^{\infty} E_\ell d\Gamma}{\int_{E_{cut}}^{\infty} d\Gamma}$

- **Hadron Mass Moments :** $M_X^{(n=1,2,3,4)} = \frac{\int_{E>E_{cut}} m_X^n d\Gamma}{\int_{E_{cut}}^{\infty} d\Gamma}$

Inclusive $\mathcal{B}(B \to X_c \ell \nu)$

◇ **Electron Energy Spectrum : di-lepton tag technique**

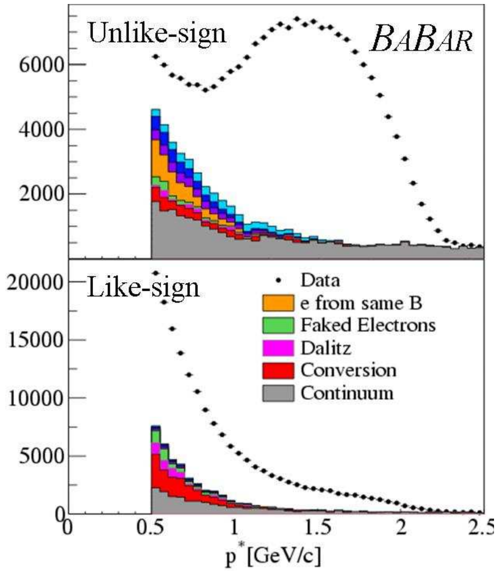
BABAR: 47 fb^{-1} (on-resonance) (PRD-RC 69, 111104, 2004)

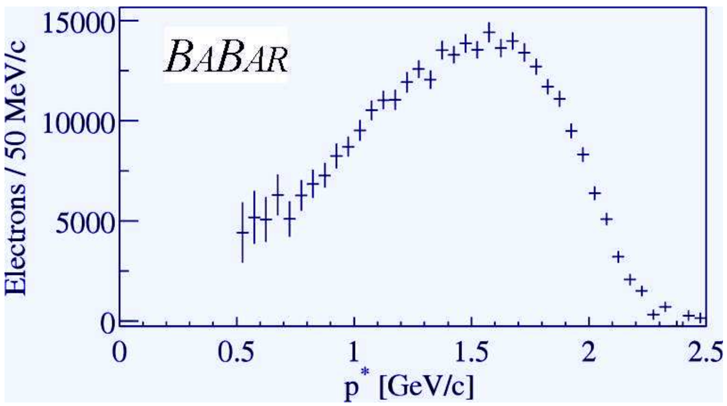
☐ **Select events with 2 electrons :**

- **One electron ($1.4 < p^* < 2.3$ GeV) to tag a $B\overline{B}$ event**
- **The other electron ($p^* > 0.5$ GeV) to measure the electron spectrum**

☐ **Measure partial $\mathcal{B}$ and the moments for $E_e > 0.6$ GeV :**

account for $B^0\overline{B}^0$ mixing, correct for Bremsstrahlung, Final State Radiation and subtract $B \to X_u \ell \nu$ background





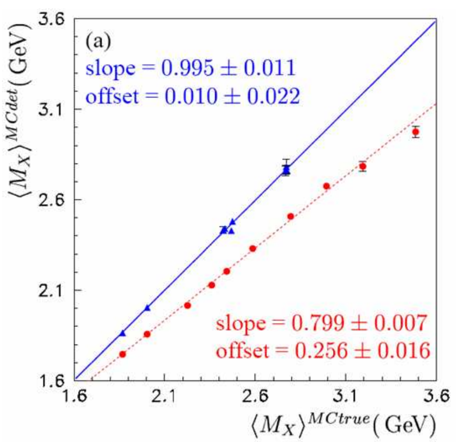
$$\mathcal{B}(B \to X_c \ell \nu) = (10.36 \pm 0.06_{stat} \pm 0.23_{sys})\%$$

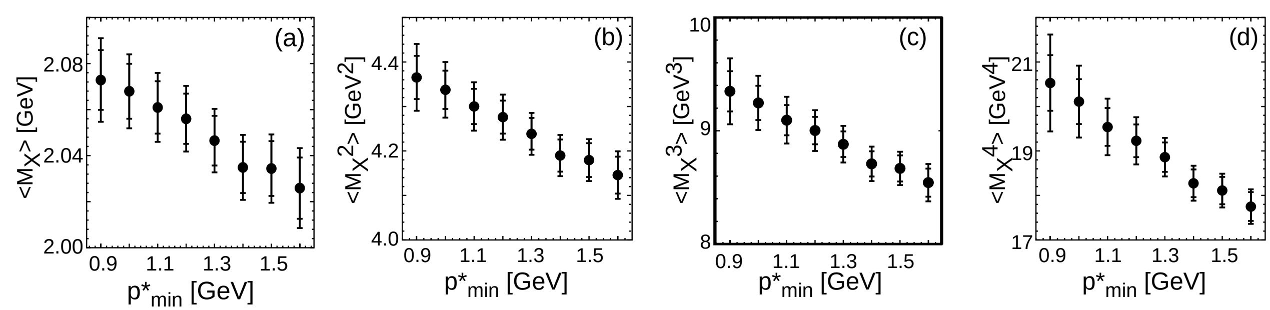
Hadronic Mass Moments

♢ Tag the events with a fully-reconstructed hadronic B decays and find leptons with $E_\ell > E_{cut}$ in the recoil B mesons

BABAR: 81 fb^{-1} (on-resonance) (PRD-RC 69, 111103, 2004)

- Measured moments ($\langle M_X^n \rangle$) are calibrated with MC events ($\langle M_X^{n\,true} \rangle$) to eliminate its dependency on unknown masses of high charm states
- Validate calibration procedure with inclusive MC $B \to X_c \ell \nu$

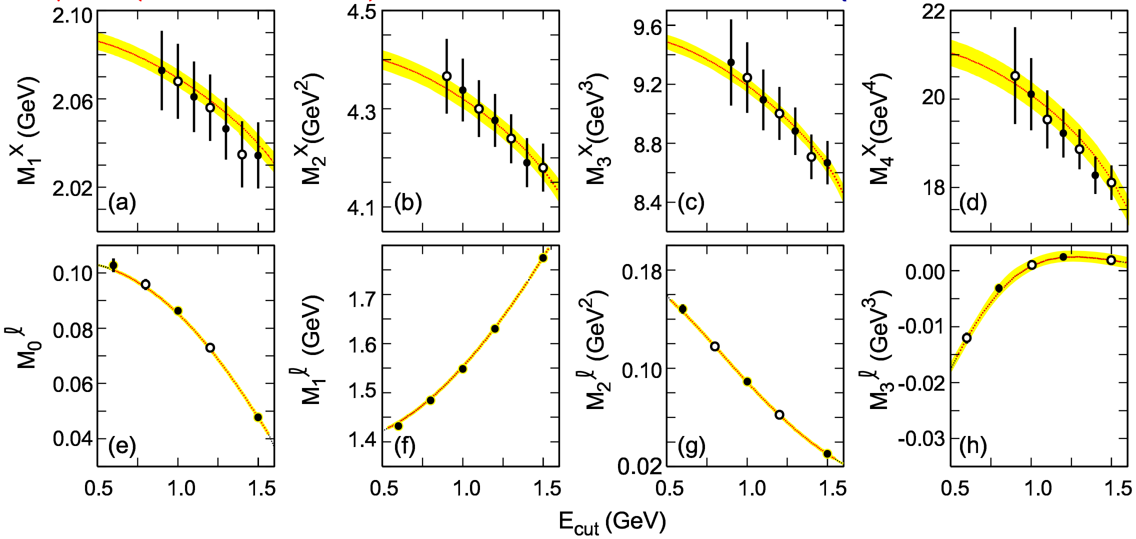




- First four moments : (a) $\langle M_X \rangle$, (b) $\langle M_X^2 \rangle$, (c) $\langle M_X^3 \rangle$, (d) $\langle M_X^4 \rangle$ w.r.t. lepton momentum (p^*_{min}) $\Longrightarrow$ they are highly correlated (right plots)
- The measured moments, $\langle M_X^n \rangle$, increase as p^*_{min} decreases $\Longrightarrow$ due to the presence of higher mass charm states

Global OPE Fits

♢ Using previous hadron mass, electron energy moments measurements, kinetic mass scheme ($\mu = 1$ GeV) by Gambino & Uraltsev (Eur. Phy. J. C34, 181, 2004), we extract $|V_{cb}|$, $\mathcal{B}(B \to X_c \ell \nu)$, and other parameters (PRL 93, 011803, 2004) :



- □ Red line is OPE fit and yellow band is theory error
  1^{st} row is hadron mass moments and 2^{st} row is electron energy moments
  $\Longrightarrow$ Data and theory predictions agree very well ($\chi^2/ndf = 20/15$)

$$|V_{cb}| = (41.4 \pm 0.4_{exp} \pm 0.4_{HQE} \pm 0.6_{th}) \times 10^{-3} \quad \to \sigma(|V_{cb}|) = 2\ \%$$

$$\mathcal{B}(B \to X_c \ell \nu) = (10.61 \pm 0.16_{exp} \pm 0.06_{HQE})\% \quad \to \sigma(\mathcal{B}) = 1.6\ \%$$

- □ $m_b = (4.61 \pm 0.05_{exp} \pm 0.04_{HQE} \pm 0.02_{\alpha_s})$ GeV
- □ $m_c = (1.18 \pm 0.07_{exp} \pm 0.06_{HQE} \pm 0.02_{\alpha_s})$ GeV

Inclusive $|V_{ub}|$ (Theory)

♢ Challenging problem for $b \to u\ell\nu$ is how to suppress $b \to c\ell\nu$ background

$\frac{\Gamma(b\to u\ell\nu)}{\Gamma(b\to c\ell\nu)} \sim \frac{|V_{ub}|^2}{|V_{cb}|^2} \sim \frac{1}{50}$. One must take care the $b \to u\ell\nu$ fraction (f_u) carefully

☐ OPE framework doesn't converge e.g. near E_ℓ endpoint

☐ Non-perturbative correction is described by Shape Function (SF)
(light-cone momentum distribution of b quark inside B meson)

However, SF cannot be calculated, it has to be determined from :

- photon spectrum in $b \to s\gamma$
- hadronic and lepton spectrum in $b \to c\ell\nu$

☐ Theoretical Approaches :

- OPE with ad-hoc inclusion of SF (DFN)

  De Fazio, Neubert (JHEP 9906, 17, 1999); Kagan, Neubert (Eur. Phys. J. C7, 5, 1999)

- OPE for $M_X - q^2$ cut for minimizing the SF effect (BLL)

  Bauer, Ligeti, and Luke hep-ex/0111387

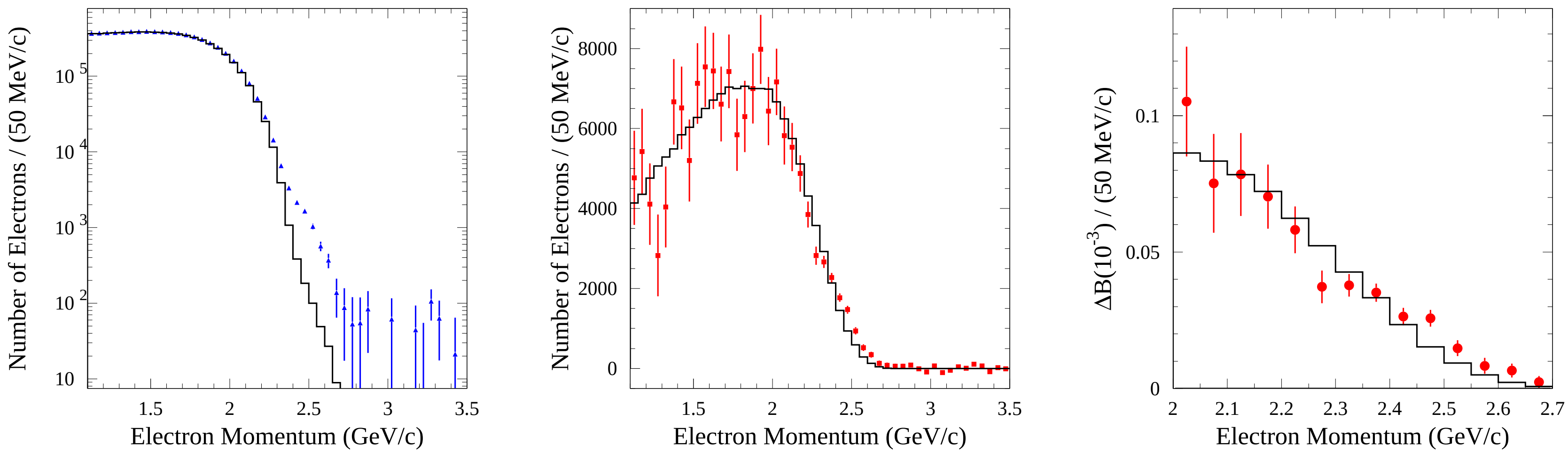
- Improved OPE that incorporates SF systematically (BLNP)

  Bosch, Lange, Neubert, Paz Nucl. Phys. B 699, 335, 2004; Lange, Neubert, Paz hep-ph/0504071

$|V_{ub}|$ from Electron Endpoint

◇ Use electrons: $2.0 < E_e < 2.6$ GeV, correct det. resolution and final-state radiation

BABAR: 80 fb^{-1} (on-resonance) (hep-ex/0509040 submited to PRD)



◇ Data & MC $B\overline{B}$ background ◇ Data & signal MC ◇ $\Delta\mathcal{B}$ vs p_e

We measure partial and total branching fractions and extract $|V_{ub}|$:

$$\boxed{\Delta\mathcal{B}(B \to X_u \ell\nu) = (0.572 \pm 0.041_{stat} \pm 0.065_{sys}) \times 10^{-3}}$$

$$\boxed{\mathcal{B}(B \to X_u \ell\nu) = (2.27 \pm 0.26_{exp}\, {}^{+0.33}_{-0.28}{}_{SF} \pm 0.17_{th-BLNP}) \times 10^{-3}}$$

$$\boxed{|V_{ub}| = (4.44 \pm 0.25_{exp}\, {}^{+0.42}_{-0.38}{}_{SF} \pm 0.22_{th-BLNP}) \times 10^{-3}} \to \sigma \sim 12\ \%$$

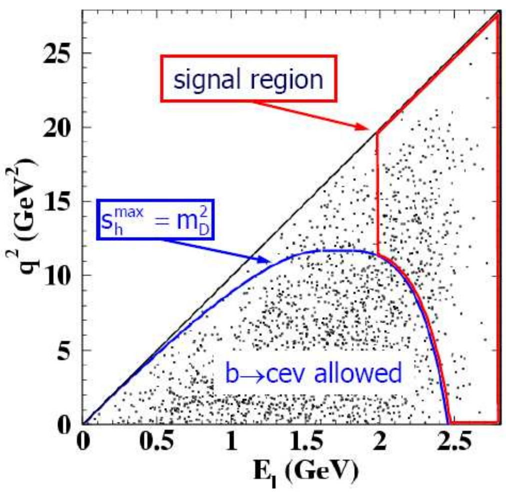
◇ SF parameters are based on $b \to c\ell\nu$ and $b \to s\gamma$ from BABAR

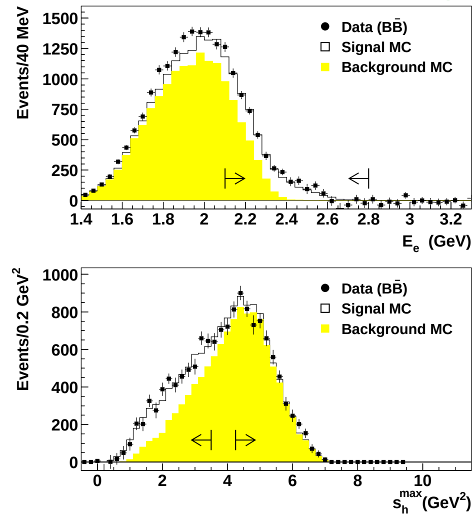
$|V_{ub}|$ from $(E_\ell - q^2)$

◇ Energy electrons: $E_e > 2.0$ GeV, with electron-neutrino reconstruction

BABAR: 81 fb^{-1} (on-resonance) (PRL 95, 111801, 2005)

◇ Estimate $b \to c\ell\nu$ from $b \to u\ell\nu$ using maximum hadronic mass squared (S_h^{max})





◇ Signal : $E_e > 2.1$ GeV, $S_h^{max} < 3.5$ GeV^2, $B\overline{B}$ bkg : $S_h^{max} > 4.25$ GeV^2

$$\Delta\mathcal{B}(B \to X_u \ell\nu) = (0.354 \pm 0.033_{stat} \pm 0.034_{sys}) \times 10^{-3}$$

□ $|V_{ub}|$ is extracted from $|V_{ub}| = \sqrt{\Delta\mathcal{B}/(\Delta\zeta \times \tau_B)}$,

$\Delta\zeta$ is normalized partial rate and $\tau_B = 1.604 \pm 0.023$ ps

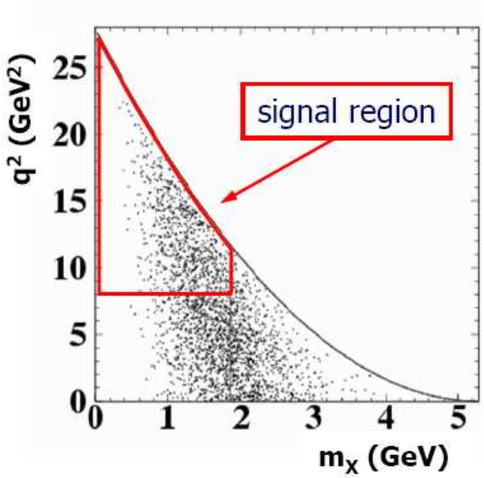
$$|V_{ub}| = (3.95 \pm 0.26_{exp} \, {}^{+0.58}_{-0.42}{}_{SF} \pm 0.25_{th-BLNP}) \times 10^{-3}$$ $\to \sigma \sim 17\ \%$

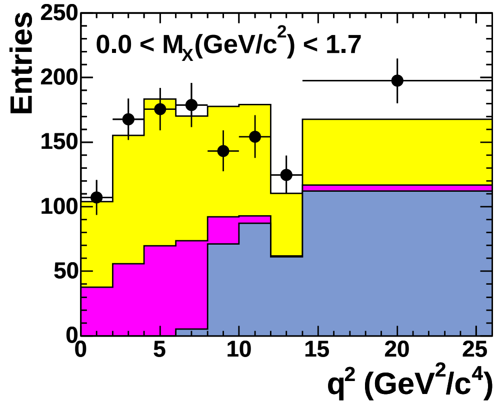
◇ SF parameters are based on $b \to c\ell\nu$ moments from BABAR

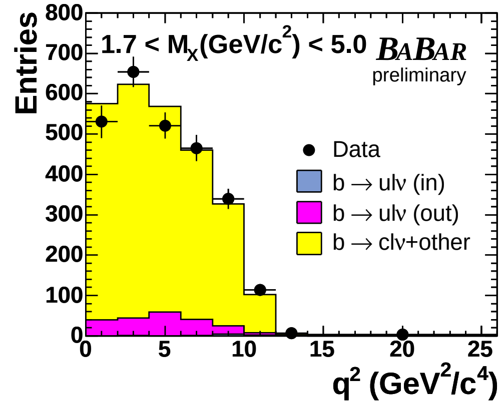
$|V_{ub}|$ from $(M_X - q^2)$

◇ Select events with a fully reconstructed B and study recoil B

BABAR: 211 fb^{-1} (on-resonance) (hep-ex/0507017 for LP2005)







◇ Signal region : $M_X < 1.7$ GeV, $q^2 > 8$ GeV^2, blue is $b \to u\ell\nu$ inside signal region

$$\Delta\mathcal{B}(B \to X_u\ell\nu) = (0.87 \pm 0.09_{stat} \pm 0.09_{sys} \pm 0.01_{th}) \times 10^{-3}$$

$$|V_{ub}|^{BLL} = (4.82 \pm 0.26_{stat} \pm 0.25_{sys} \pm 0.46_{SF+th}) \times 10^{-3} \quad \sigma \sim 12\ \%$$

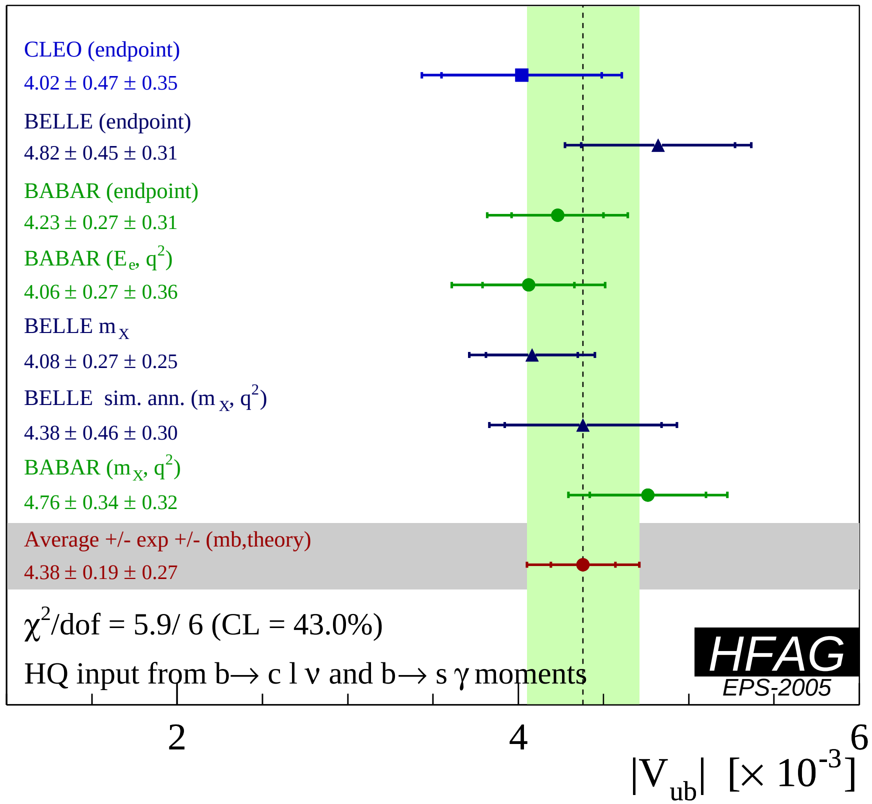
$$|V_{ub}|^{BLNP} = (4.65 \pm 0.24_{stat} \pm 0.24_{sys}\ {}^{+0.46}_{-0.38}{}_{SF} \pm 0.23_{th}) \times 10^{-3} \quad \sigma \sim 13\ \%$$

◇ SF parameters are based on $b \to c\ell\nu$ from BABAR

Inclusive $|V_{ub}|$ (Summary)

♢ New BABAR electron endpoint result is not in this summary yet

$$\Longrightarrow |V_{ub}| = (4.44 \pm 0.25_{exp} {}^{+0.42}_{-0.38}{}_{SF} \pm 0.22_{th-BLNP}) \times 10^{-3}$$



$$|V_{ub}|_{Avg} = (4.38 \pm 0.19_{exp} \pm 0.27_{[m_b,th]}) \times 10^{-3}$$

$$\mathcal{B}(B \to X_u \ell \nu)_{Avg} = (2.18 \pm 0.33) \times 10^{-3}$$

Exclusive $|V_{ub}|$ and $|V_{cb}|$

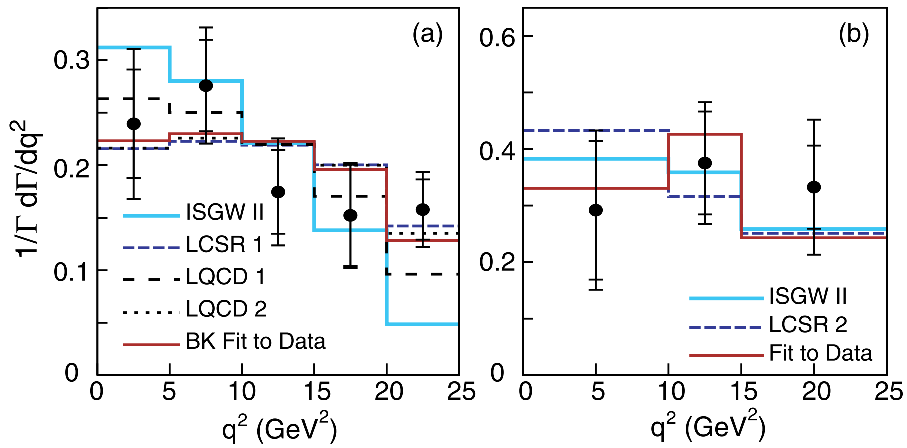
◇ Determination of exclusive $|V_{ub}|$ and $|V_{cb}|$ is complicated due to strong interaction effects

These effects may be parameterized by Form Factors (squared four-momentum transfer)

☐ BABAR measurements on exclusive $|V_{ub}|$:

- Neutrino reconstruction (76/fb) : (PRD-RC 72, 051102, 2005)

  Modes : $(B^0 \to \pi^- \ell^+ \nu)$ & $(B^0 \to \rho^- \ell^+ \nu)$; $|p^*_\ell| > 1.3$ GeV, π/ρ, $|p_{miss}| > 0.7$ GeV



◇ q^2 with form-factor predictions : (a) $B^0 \to \pi^- \ell^+ \nu$ (b) $B^0 \to \rho^- \ell^+ \nu$

$$|V_{ub}| = (3.82 \pm 0.14_{stat} \pm 0.22_{sys} \pm 0.11_{q^2} \,{}^{+0.88}_{-0.52}{}_{FF}) \times 10^{-3}$$

- Semileptonic B decays :

  $\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu) = (1.80 \pm 0.37_{stat} \pm 0.23_{sys}) \times 10^{-4}$, (81/$fb$) (hep-ex 0506065)

  $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.03 \pm 0.25_{stat} \pm 0.13_{sys}) \times 10^{-4}$, (211/$fb$) (hep-ex 0506064)

$$|V_{ub}| = (3.3 \pm 0.4_{stat} \pm 0.2_{sys} \,{}^{+0.8}_{-0.4}{}_{FF}) \times 10^{-3}$$

Exclusive $|V_{ub}|$ and $|V_{cb}|$

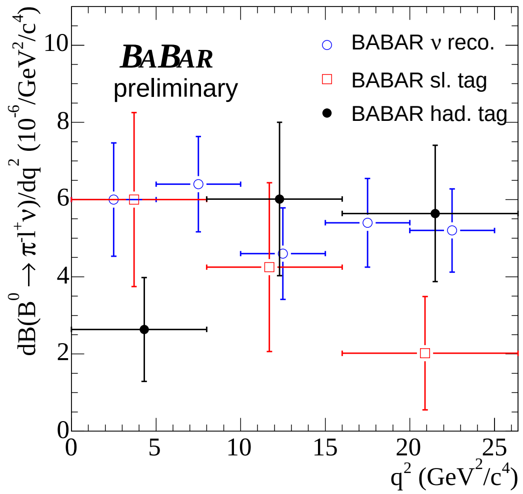
- Fully hadronic recoil ($211/fb$) : [q^2 resolution (0.25-0.50 GeV^2)] (hep-ex 0507085)

  Selection : $q^2 < 8$ GeV^2, 8-16 GeV^2, $q^2 > 16$ GeV^2; $p^*_\ell > 0.5$ GeV, $p^*_\mu > 0.8$ GeV

  $$\mathcal{B}(B^0 \to \pi^-\ell^+\nu) = (1.14 \pm 0.27_{stat} \pm 0.17_{sys}) \times 10^{-4}$$
  $$\mathcal{B}(B^+ \to \pi^0\ell^+\nu) = (0.86 \pm 0.22_{stat} \pm 0.11_{sys}) \times 10^{-4}$$

  $$\boxed{|V_{ub}| = (3.7 \pm 0.3_{stat} \pm 0.2_{sys}\ {}^{+0.8}_{-0.5}{}_{FF}) \times 10^{-3}}$$

  ♢ Compare with other BABAR measurements :



- BABAR measurement on exclusive $|V_{cb}|$: (PRD-RC 71, 051502, 2005)

  • $\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell) = (4.90 \pm 0.07_{stat}\ {}^{+0.36}_{-0.35}{}_{sys})\%$ ($79/fb$)

  Using LQCD calculation : $\mathcal{A}_1 = \mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$ (PRD 66, 014503, 2002)

  $$\boxed{|V_{cb}| = (38.7 \pm 0.3_{stat} \pm 1.7_{sys}\ {}^{+1.5}_{-1.3}{}_{th}) \times 10^{-3}}$$

Summary

- A precision measurement of $\frac{|V_{ub}|}{|V_{cb}|}$ would significantly improve the constraints on the Unitary Triangle in SM

  $\Longrightarrow$ It could benchmark for New Physics

- Current precision of $|V_{ub}|$ and $|V_{cb}|$ measurements :

  - $(\frac{\Delta|V_{ub}|}{|V_{ub}|}) = (3.3_{exp} \pm 2.9_{model} \pm 4.7_{SF} \pm 4.0_{th})\% = 7.6\%$
  - $(\frac{\Delta|V_{cb}|}{|V_{cb}|}) =$ 2%. (OPE fit of E_ℓ and M_X moments by BABAR)

  $\Longrightarrow$ It contributes directly to a precision of $(\frac{\Delta|V_{td}|}{|V_{td}|})$

- BABAR is aiming to measure $(\frac{\Delta|V_{ub}|}{|V_{ub}|}) = 5\%$

  The current theoretical limit is $\sim 5\%$

- BABAR will double the data by summer 2006 (0.5 ab^{-1})

  We hope to quadruple the data by 2008 (1 ab^{-1})